L6 Assembly - Functions

EECS 370 – Introduction to Computer Organization – Winter 2022

L6_1 Assembly - Functions

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Learning Objectives

- Understand how program data, particularly at the granularity of a function, maps to memory
- Identify data passed between functions and the mapping of that data to memory

Schedule Reminders

- Homework 2 is due Monday 2/7
  - A homework assignment is usually released soon after the previous one is due
- Project 1s and 1m due Thursday 2/3

Call and Return

```
Address:    void foo()
            {
    1000      int x = 5;
    1004      bar();
    1008      x = x + 1;
    1012      return;
            }

            void bar()
            {
    3000      int y = 10;
    3004      return;
            }
```

Order of execution:	Notes:
`int x = 5;`	
`bar();`	`// branch to 3000`
`int y = 10;`	
`return;`	`return; // branch to 1008`
`x = x + 1;`	
`return;`	`return; // branch to ???`

Remember:	`void baz()`

There can be many call sites for a function in a program, i.e., more than just `foo()` will call `bar()`	`{`
	`  bar();`
	`  return;`
	`}`

Unconditional Branching Instructions

ARM Branching

Unconditional branch	branch	B 2500	go to PC + 10000	Branch to target address; PC-relative
	branch to register	BR X30	go to X30	For switch, procedure return
	branch with link	BL 2500	X30 = PC + 4; PC + 10000	For procedure call PC-relative

How we return from the function.

use this for function call

link register

jump to the target

where we come back to after we make the function call

- There are three types of unconditional branches in the LEGv8 ISA.
  - The first **(B)** is the PC relative branch with the 26-bit offset from the last slide.
  - The second **(BR)** jumps to the address contained in a register (X30 above)
  - The third **(BL)** is like our PC relative branch but it does something else.
    - It sets X30 (always) to be the current PC+4 before it branches.
    - Why?
    - Function calls – return to next instruction

Branch with Link (BL)

ARM Branching

- Branch with Link is the branch instruction used to call functions
  - Functions need to know where they were called from so they can return.
    - In particular they will need to return to right after the function call
    - Can use "BR X30"

- Say that we execute the instruction `BL #500` when at PC `1000`.
  - What address will be branched to? 3000
  - What value is stored in X30? 1000+4 = 1004
  - How is that value in X30 useful?

1000 + 500X4 = since each instruction is 4 bytes
= 1000 + 2000
= 3000

Converting function calls to assembly code

Function Calls

C code: `factorial(5);`

1. Need to pass arguments (5) to the called function (`factorial()`)
2. Need to save return address of the caller
3. Need to save register values
4. Need to jump to factorial (callee)

1. Need to get return value (for non-`void` return type)
2. Need to restore register values

Task 1: Passing Arguments

Function Calls

- Where should you put all the arguments?
  - Registers?
    - Fast access but few in number and wrong size for some objects
  - Memory?
    - Good general solution but slow
- ARMv8 solution—and the usual answer:
  - Registers and memory
    - Put the first few arguments in registers (if they fit) (X0 – X7)
    - Put the rest in memory on the call stack— important concept
- Comment: Make sure you understand the general idea behind a stack data structure—ubiquitous in computing
  - As basic concept it is a list in that you can only access at one end by pushing a data item into the top of the stack and popping an item off of the stack—real stacks are a little more complex

ABI : Application Binary Interface

Call stack

- ARM conventions (and most other processors) allocate a region of memory for the "call" stack
  - This memory is used to manage all the storage requirements to simulate function call semantics

    - Parameters (that were not passed through registers)
    - Local variables
    - Temporary storage (when you run out of registers and need somewhere to save a value)
    - Return address
    - etc.

- Sections of memory on the call stack [a.k.a. **stack frames**] are allocated when you make a function call, and de-allocated when you return from a function—the stack frame is a fixed template of memory locations

is private for the certain function

An Older ARM (Linux) Memory Map

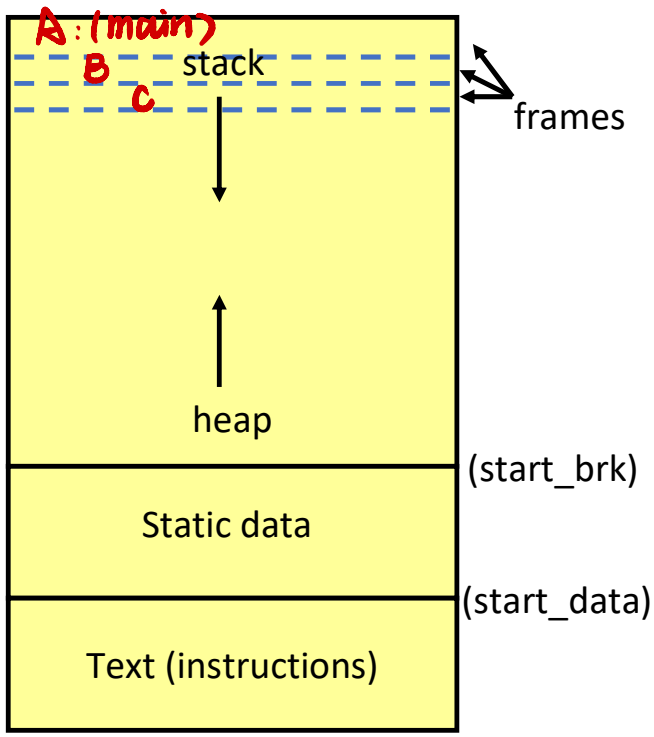
Function Calls

Stack: starts at `0x0000 007F FFFF FFFC` and grows down to lower addresses. Bottom of the stack resides in the SP register

Heap: starts above static data and grows up to higher addresses. Allocation done explicitly with malloc(). Deallocation with free(). Runtime error if no free memory before running into SP address.

Static: starts above text. Holds all global variables and those locals explicitly declared as "static".

Text: starts at `0x0000 0000 0004 0000`. Holds all instructions in the program (except for dynamically linked library routines, DLLs)



Assigning variables to memory spaces

Function Calls

```
int w;
void foo(int x)
{
  static int y[4];
  char *p;
  p = malloc(10);

  // more instructions

  printf("%s\n", p);

  return;
}
```

w goes in static, as it is a global

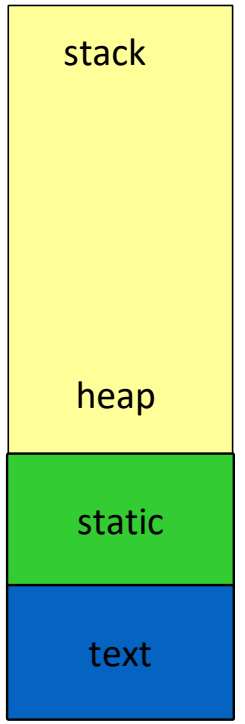
x goes on the stack, as it is a parameter

y goes in static, 1 copy of this!!

p goes on the stack

allocate 10 bytes on heap, p set to the address

string goes in static with a pointer to string on stack, p goes on stack



global variable

the parameter is local to the function

argument

means "y" is a global variable that only "foo" can see

local variable

(they don't have name)

String constant

constant is in global section. → Static

stack.

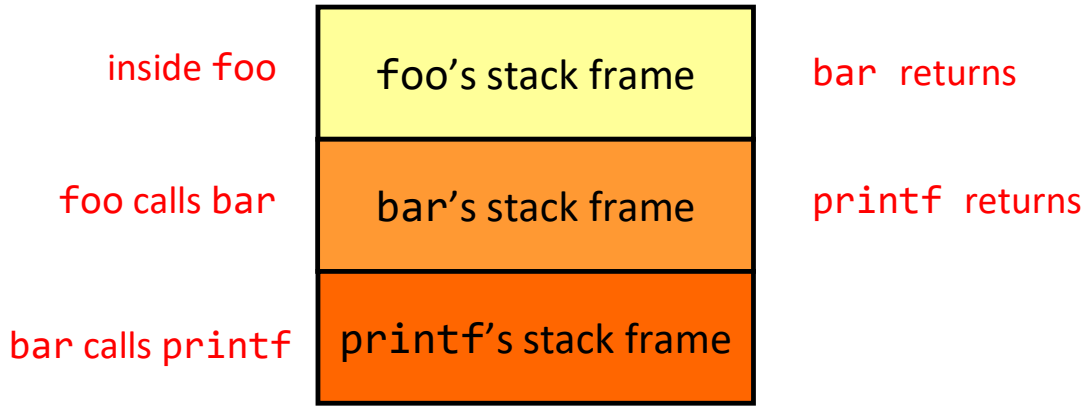
if two functions have the same String constant,

the compiler will store them together at global section → static

The stack grows as functions are called

Function Calls

```
void foo()
{
  int x, y[2];
  bar(x);
}

void bar(int x)
{
  int a[3];
  printf();
}
```



once foo() call bar(x). foo static frame will be nonactive, and bar static frame will be active

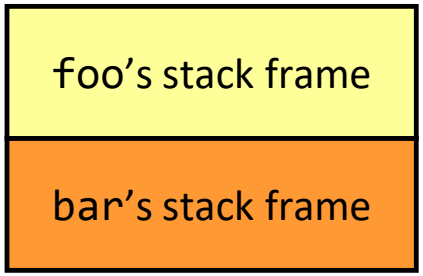
The stack grows as functions are called

Function Calls

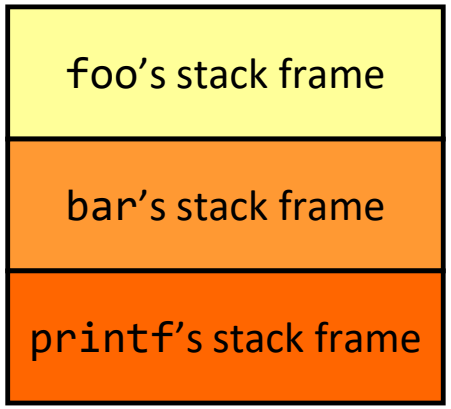
```
void foo()
{
  int x, y[2];
  bar(x);
}

void bar(int x)
{
  int a[3];
  printf();
}
```

inside foo

foo calls bar



bar calls printf

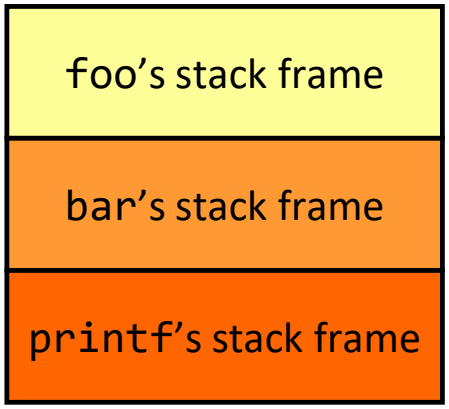


The stack shrinks as functions return

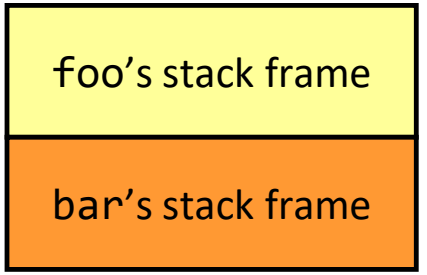
Function Calls

```
void foo()
{
  int x, y[2];
  bar(x);
}

void bar(int x)
{
  int a[3];
  printf();
}
```

In `printf`



`printf` returns to bar



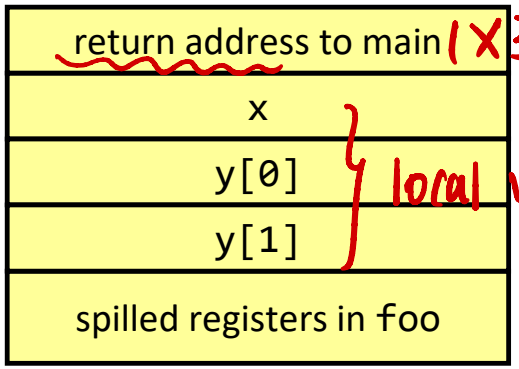
`bar` returns to `foo`

Stack frame contents (0)

Function Calls

```
void foo()
{
  int x, y[2];
  bar(x);
}

void bar(int x)
{
  int a[3];
  printf();
}
```

foo's stack frame



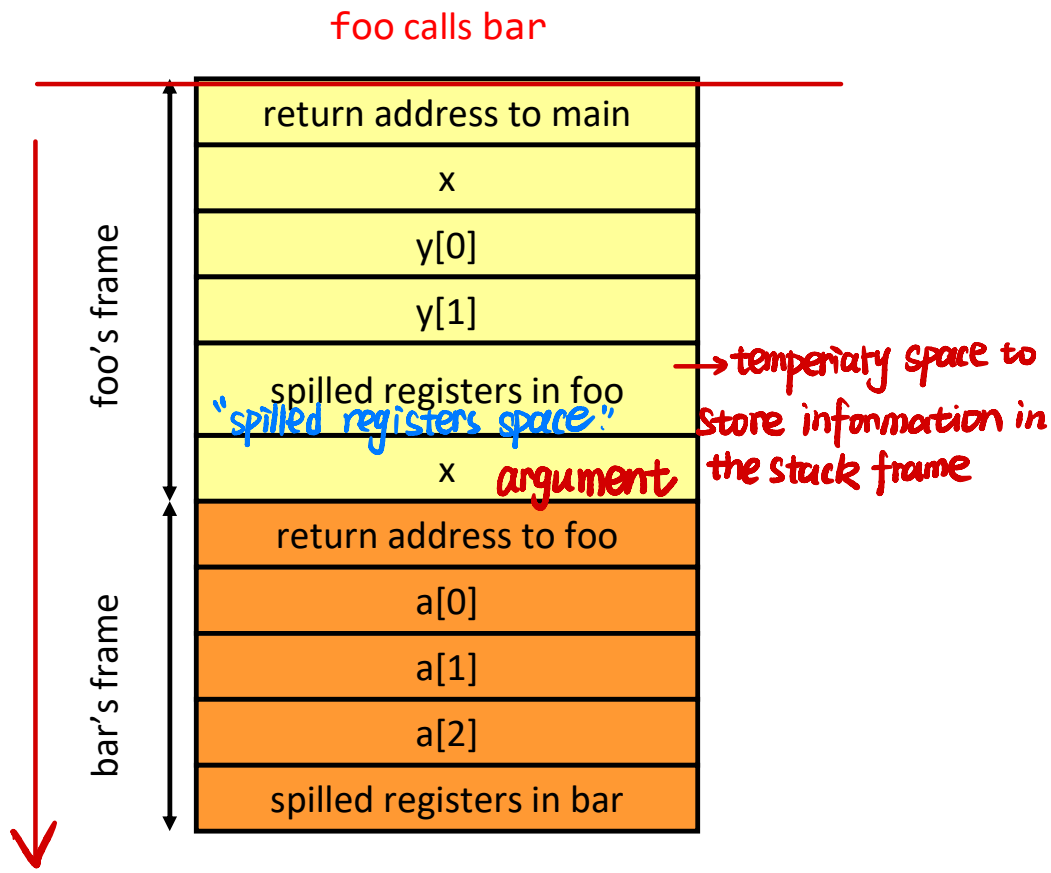
(X30) where we go back to when we are done.

local variable.

Stack frame contents (1)

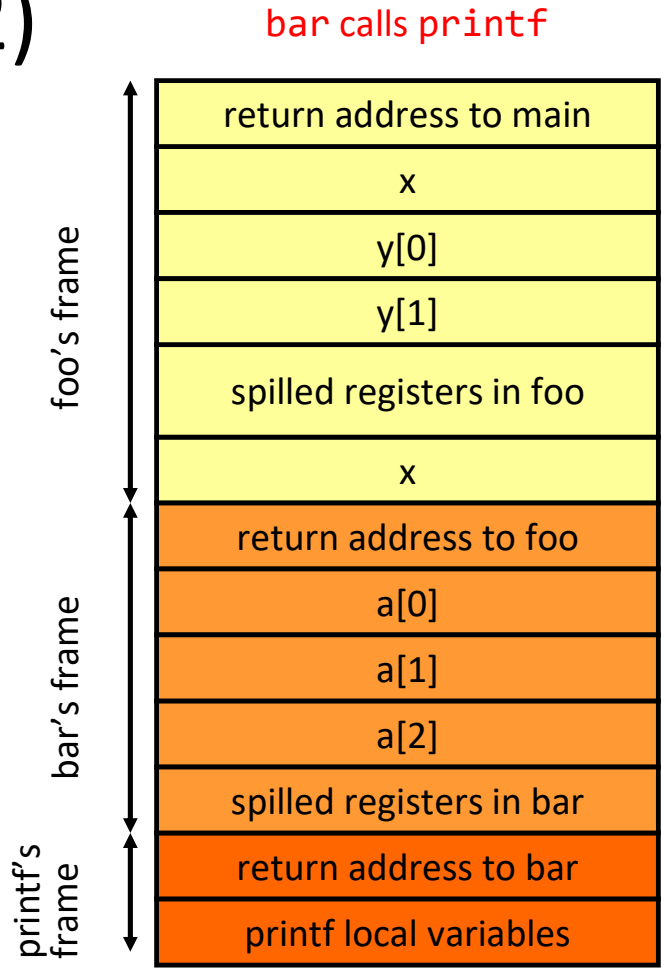
Function Calls

```
void foo()
{
  int x, y[2];
  bar(x);
}

void bar(int x)
{
  int a[3];
  printf();
}
```



Stack frame contents (2)


```
void foo()
{
  int x, y[2];
  bar(x);
}

void bar(int x)
{
  int a[3];
  printf();
}
```



Recursive function example


```
void main()
{
  foo(2);
}

void foo(int a)
{
  int x, y[2];
  if (a > 0)
  {
    foo(a-1);
  {
}
```

main calls foo

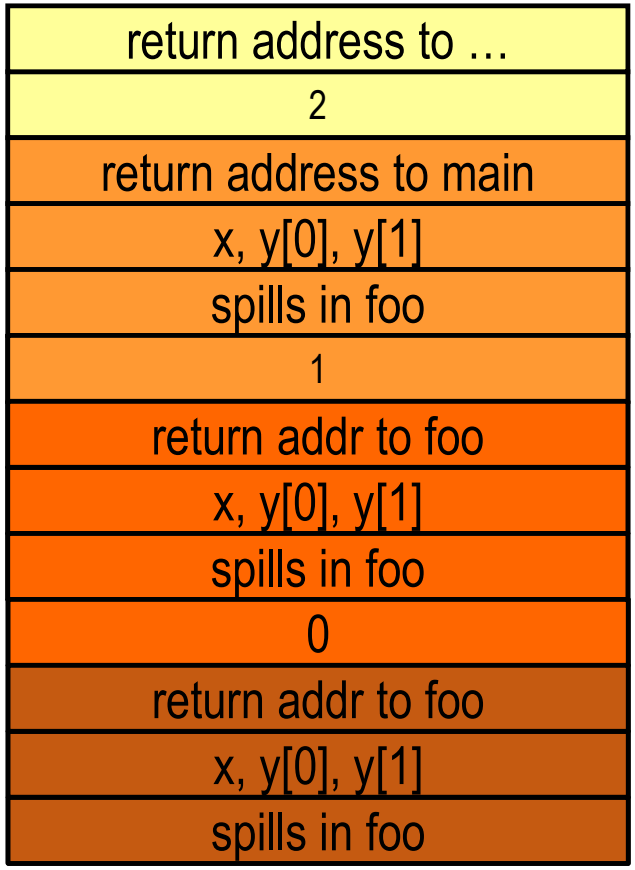
foo(2)

foo calls foo

foo(1)

foo calls foo

foo(0)



L6_2 Caller/Callee Saved Registers

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Each function has their own local stack frame & local variable.

But they need to share 32 registers.

Learning Objectives

- Understand how program data, particularly at the granularity of a function, maps to registers
- Identify data passed between functions and the mapping of that data to registers

What about values in registers?

- When function “foo” calls function “bar”, function “bar” is, like all assembly code, going to store some values in registers.
- But function “foo” might have some values stored in registers that it wants to use after the call.
  - How can “foo” be sure “bar” won’t overwrite those values?
  - One answer: “foo” could save those values to memory (on the stack) before it calls “bar”.
    - Now “bar” can freely use registers
  - And “foo” will have to copy the values back from memory once “bar” returns.
- In this case the “caller” (foo) is saving the registers to the stack.

```
foo: addi x0, x0, #1
     bl bar
     add  x1, x0, x2
```

```
bar: movz x0, #3000
```

Register Spilling Example

definition.

> The process of putting less frequently used variables (or those needed later) into memory is called **spilling** registers

Caller-Callee

Find a left variable, and point to the right same variable.

```
void foo(){
  int a,b,c,d;
  a = 5;
  b = 6;
  c = a+1;
  d=c-1;

  bar();

  d = a + d;
  return;
}
```

b never alive.

a live across bar() means: I define a above bar(), and use it after it.

- The function foo is going to have values a, b, c, and d kept in registers.
  - For sake of argument, let's say that "a" is stored in X1, "b" in X2, etc.
- When foo calls bar, bar might end up writing to some of the same registers that foo is using.
  - In this case, if bar were to change the value of X1 (which holds a) or X4 (which holds d) then foo wouldn't behave correctly.
- **What we need is some way to ensure that when we call a function, it will not "trash" values we need after the call**
  - Definition: a value that is defined before a function call and needed after a function call is said to be "**live**" across the function call.

liveness analysis: to know which variable we need to store

One solution: Caller Save


```
void foo(){
  int a,b,c,d;
  a = 5;
  b = 6;
  c = a+1;
  d=c-1;
  save X1 to stack
  save X4 to stack
  bar();
  restore X1 from stack
  restore X4 from stack
  d = a + d;
  return;
}
```

a → x1
b → x2
c → x3
d → x4

will use foo's register to do work.

- Anytime one function calls another function, the caller should first save to the stack any registers whose values it might need later.
  - After returning, those values will be copied back from the stack into their original register.
  - Now the "callee" function will not overwrite values its "caller" still needs.
  - We call this option **"caller save"**

save before the call and restore after the call

- Again, let's assume that a is stored in X1, b in X2, etc.
  - If we are using this "caller-save" option
    - What registers do we need to save to the stack before calling bar?
    - What registers do we need to restore from the stack?

Caller:
the function that call someothen function

Caller-Callee

Another solution: Callee Save

The function that been called. (bar)

```
void foo(){
  int a,b,c,d;


  a = 5;
  b = 6;
  c = a+1;
  d=c-1;

  bar();

  d = a + d;


  return;
}
```

- We could instead have each function save every register it is going to use before it does anything else.
  - Again, let's assume a is in X1, b in X2, etc.

- In this case, we'd save X1, X2, X3, and X4 before we did anything else and then restore them at the end of the function.
  - Thus whatever function called "foo" would be sure its registers wouldn't get trashed by foo as foo would save and restore all registers.
  - All functions would do the same thing.
    - so foo's values in X1 and X4 are safe from bar trashing them.

Another solution: Callee Save

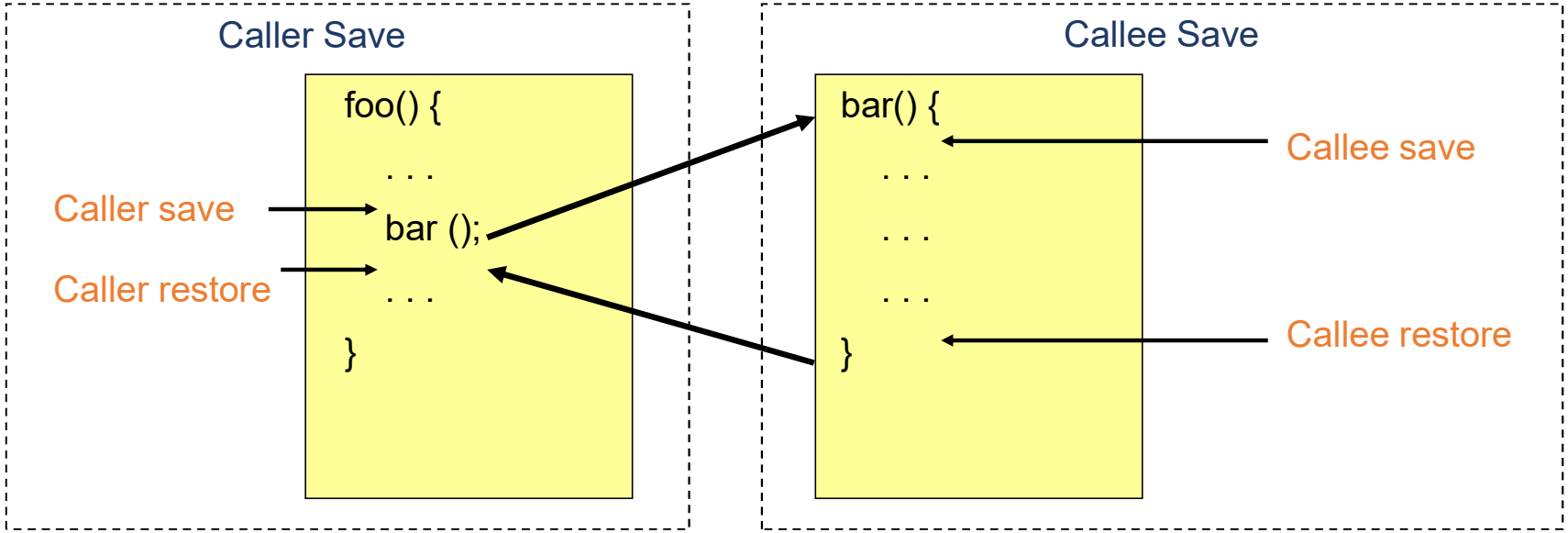

```
void foo(){
  int a,b,c,d;
  save X1, X2, X3, X4
    to stack
  a = 5;
  b = 6;
  c = a+1;
  d=c-1;

  bar();

  d = a + d;
  restore X1, X2, X3, X4
    from stack

  return;
}
```

- We could instead have each function save every register it is going to use before it does anything else.
  - Again, let's assume a is in X1, b in X2, etc.
- In this case, we'd save X1, X2, X3, and X4 before we did anything else and then restore them at the end of the function.
  - Thus whatever function called "foo" would be sure its registers wouldn't get trashed by foo as foo would save and restore all registers.
  - All functions would do the same thing.
    - so foo's values in X1 and X4 are safe from bar trashing them.

“caller-save” vs. “callee-save”

- So we have two basic options:
  1. Each function can save registers **before** you make the function call and restore the registers when you return (**caller-save**).
     - What if the function you are calling doesn’t use that register? No harm done, but wasted work!!!
  2. You can save all registers you are going to use at the very start of each function (**callee-save**).
     - What if the caller function doesn’t need that value? No harm done, but wasted work!!!
- Most common scheme is to have some of the registers be the responsibility of the caller, and others be the responsibility of the callee.

Caller-Callee Save/Restore



Caller save registers: Callee may change, so caller responsible for saving immediately before call and restoring immediately after call

Callee save registers: Must be the same value as when called. May do this by either not changing the value in a register or by inserting saves at the start of the function and restores at the end

Saving/Restoring Optimizations

- Caller-saved
  - Only needs saving if it is "live" across a function call
  - Live = contains a useful value: Assign value before function call, use that value after the function call
  - In a leaf function (a function that calls no other function), caller saves can be used without saving/restoring
- Callee-saved
  - Only needs saving at beginning of function and restoring at end of function
  - Only save/restore it if function overwrites the register
- Each has its advantages. Neither is always better.

Calling Convention

- This is a **convention**: calling convention
  - There is no difference in H/W between caller and callee save registers

- Passing parameters in registers is also a convention
- Allows assembly written by different people/compilers to work together
  - Need conventions about who saves regs and where args are passed.
- These conventions collectively make up the ABI or “application binary interface”

- Why are these conventions important?
  - What happens if a programmer/compiler violates them?

Caller/Callee Selection

- Select assignment of variables to registers such that the sum of caller/callee costs is minimized
  - Execute fewest save/restores
- Each function greedily picks its own assignment ignoring the assignments in other functions
  - Calling convention assures all necessary registers will be saved
- 2 types of problems
  - Given a single function → Assume it is called 1 time
  - Set of functions or program → Compute number of times each function is called if it is obvious (i.e., loops with known trip counts or you are told)

only care about one single function at one time

Don't care about loop

Assumptions

- A function can be invoked by many different call sites in different functions.

- Assume no inter-procedural analysis (hard problem)
  - A function has no knowledge about which registers are used in either its caller or callee
  - Assume main() is not invoked by another function

- Implication
  - Any register allocation optimization is done using function local information

L6_3 Caller/Callee Examples

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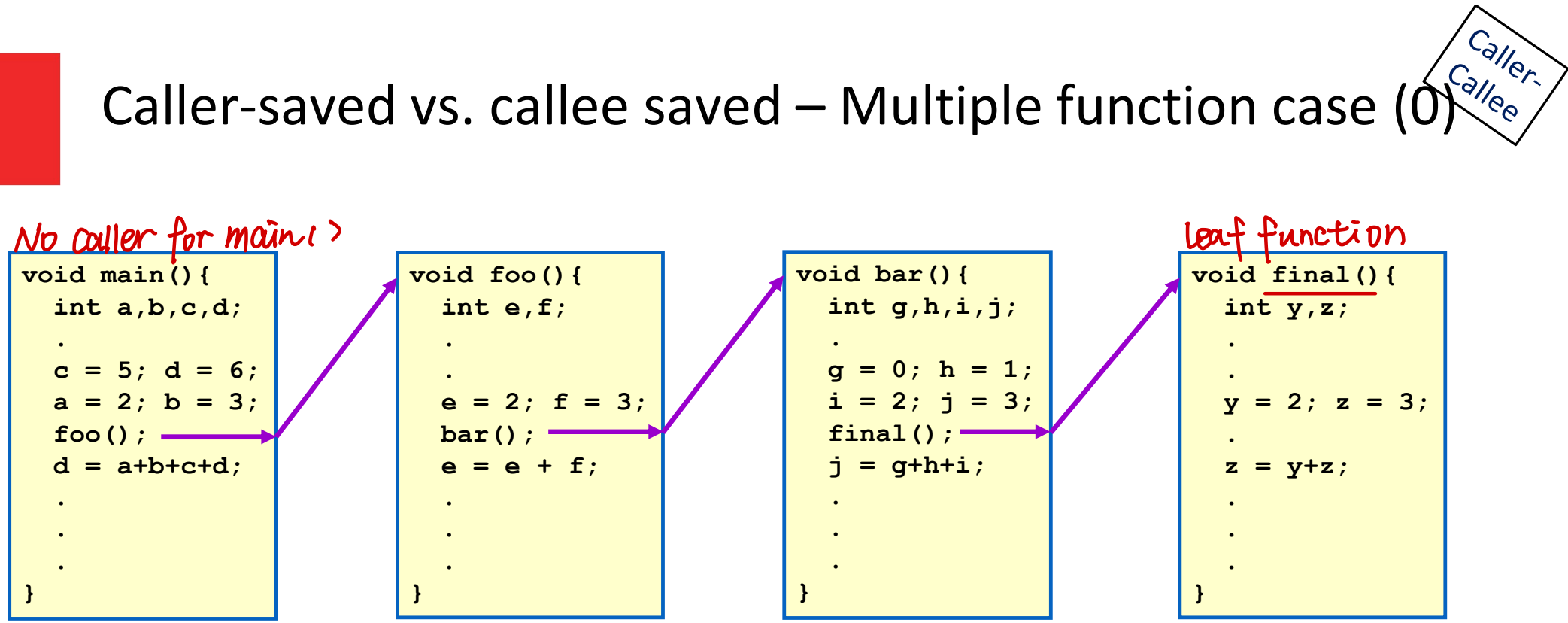
Learning Objectives

- Identify trade-offs between caller-save, callee-save, and mixed caller/callee-save register spilling
- Understanding of how to apply caller/callee/mixed register spilling to arbitrary functions and programs

Caller-saved vs. callee saved – Multiple function case (0)



Note: assume main does not have to save any callee registers

Caller-saved vs. callee saved – Multiple function case (1)

- Questions:
  1. In assembly code, how many registers need to be stored/loaded in total if we use a **caller-save** convention ?

     6 caller
  2. In assembly code, how many registers need to be stored/loaded in total if we use a **callee-save** convention ?

     6 callee
  3. In assembly code, how many registers need to be stored/loaded in total if we use a mixed **caller/callee**-save convention with **3 callee** and **3 caller** registers ?

Question 1: Caller-Save

Caller-Callee

```
void main(){
  int a,b,c,d;
  .
  c = 5; d = 6;
  a = 2; b = 3;
  [4 STURW]
  foo();
  [4 LDURSW]
  d = a+b+c+d;
  .
  .
  .
}
```

```
void foo(){
  int e,f;
  .
  .
  e = 2; f = 3;
  [2 STURW]
  bar();
  [2 LDURSW]
  e = e + f;
  .
  .
  .
}
```

```
void bar(){
  int g,h,i,j;
  .
  g = 0; h = 1;
  i = 2; j = 3;
  [3 STURW]
  final();
  [3 LDURSW]
  j = g+h+i;
  .
  .
  .
}
```

```
void final(){
  int y,z;
  .
  .
  y = 2; z = 3;
  .
  z = y+z;
  .
  .
  .
}
```

Total: 9 STURW / 9 LDURSW

9 store / 9 Load

Question 2: Callee-Save

Caller-Callee

```
void main(){
  int a,b,c,d;
  .
  c = 5; d = 6;
  a = 2; b = 3;
  foo();
  d = a+b+c+d;
  .
  .
  .
}
```

```
void foo(){
  [2 STURW]
  int e,f;
  .
  .
  e = 2; f = 3;
  bar();
  e = e + f;
  .
  .
  .
  [2 LDURSW]
}
```

```
void bar(){
  [4 STURW]
  int g,h,i,j;
  .
  g = 0; h = 1;
  i = 2; j = 3;

  final();

  j = g+h+i;
  .
  [4 LDURSW]
}
```

```
void final(){
  [2 STURW]
  int y,z;
  .
  .
  y = 2; z = 3;
  .
  z = y+z;
  .
  .
  [2 LDURSW]
}
```

Total: 8 STURw / 8 LDURSW

Note: assume main does not have to save any callee registers

Caller-Save and Callee-Save Registers(0)

- Again, what we really tend to do is have some of the registers be the responsibility of the caller and others the responsibility of the callee.
  - So if you have ***six registers***, then `X0-X2` are caller-save registers and `X3-X5` are callee-save registers.

These will never change

- How does that help?

X0-X2 are caller-save, X3-X5 are callee-save

Question 3: Mixed 3 Each Caller/Callee-Save

no caller

```
void main(){
  int a,b,c,d;
  .
  c = 5; d = 6;
  a = 2; b = 3;
  foo();
  d = a+b+c+d;

}
```

ee eeee er

one save

one store.

```
void foo(){

  int e,f;
  .
  .
  e = 2; f = 3;
  bar();
  e = e + f;
  .
  .
  .

}
```

```
void bar(){

  int g,h,i,j;
  .
  g = 0; h = 1;
  i = 2; j = 3;

  final();

  j = g+h+i;
  .

}
```

```
void final(){

  int y,z;
  .
  .
  y = 2; z = 3;
  .
  z = y+z;
  .
  .
}
```

X0-X2 are caller-save, X3-X5 are callee-save

Question 3: Mixed 3 Each Caller/Callee-Save

Caller-Callee

For main, we'd like to put all the variables into callee save registers. But we only have 3 callee save registers (X3-X5), so one variable needs to end up in a caller-save register.

```
void main(){
  int a,b,c,d;
  .
  c = 5; d = 6;
  a = 2; b = 3;
  [1 STURW]
  foo();
  [1 LDURSW]

  d = a+b+c+d;

}
```

Caller save: 4

Callee save: 0. (prefer).

1 caller reg.
3 callee reg.

} This is the decision only made on this local function

X0-X2 are caller-save, X3-X5 are callee-save

Question 3: Mixed 3 Each Caller/Callee-Save


```
void foo(){
   [2 STURW]
   int e,f;
   .
   .
   e = 2; f = 3;
   bar();
   e = e + f;
   .
   .
   .
   [2 LDURSW]
}
```

Caller save : 2
Callee save : 2
} same.

2 callee reg.

For foo it doesn't really matter what registers we use.
Either way we will have to save and restore 2 values

X0-X2 are caller-save, X3-X5 are callee-save

Question 3: Mixed 3 Each Caller/Callee-Save


```
void bar(){
  [3 STURW]
  int g,h,i,j;
  .
  g = 0; h = 1;
  i = 2; j = 3;

  final();

  j = g+h+i;
  .
  [3 LDURSW]
}
```

Callee save : 4

never saved

Caller save : 3.

since not live through function call.

1 caller reg.
3 callee reg.

For bar, "j" should be allocated to caller-save register. The others don't matter.

X0-X2 are caller-save, X3-X5 are callee-save

Question 3: Mixed 3 Each Caller/Callee-Save

caller save: 0 (prefer)

callee save: 2

```
void final(){

   int y,z;
   .    er er.
   .
   y = 2; z = 3;
   .
   z = y+z;
   .
   .
}
```

2 caller reg.

X0-X2 are caller-save, X3-X5 are callee-save

Question 3: Mixed 3 Each Caller/Callee-Save

For main, we'd like to put all the variables into callee save registers. But we only have 3 callee save registers (X3-X5), so one variable needs to end up in a caller-save register.

```
void main(){
  int a,b,c,d;
  .
  c = 5; d = 6;
  a = 2; b = 3;
  [1 STURW]
  foo();
  [1 LDURSW]

  d = a+b+c+d;

}
```

1 caller reg.
3 callee reg.

```
void foo(){
  [2 STURW]
  int e,f;
  .
  .
  e = 2; f = 3;
  bar();
  e = e + f;
  .
  .
  .
  [2 LDURSW]
}
```

2 callee reg.

```
void bar(){
  [3 STURW]
  int g,h,i,j;
  .
  g = 0; h = 1;
  i = 2; j = 3;

  final();

  j = g+h+i;
  .
  [3 LDURSW]
}
```

1 caller reg.
3 callee reg.

```
void final(){

  int y,z;
  .
  .
  y = 2; z = 3;
  .
  z = y+z;
  .
  .
}
```

2 caller reg.

Total: 6 STURW / 6 LDURSW

For foo it doesn't really matter what registers we use. Either way we will have to save and restore 2 values

For bar, "j" should be allocated to caller-save register. The others don't matter.

It can get quite a bit more complex than this

- Multiple function calls in a given function will make things more complex
  - As will loops
- The video review for caller/callee save found on the class website is quite useful
- 370 website → review videos
- Discussion videos also go over some examples

Assume calling something else, just use same analysis.

Does Recursion Change Caller/Callee?

Caller-Callee

- No! Treat `foo()` just like any normal function and assume you are calling an unknown function.

```
void main(){
  int a,b,c,d;
  .
  c = 5; d = 6;
  a = 2; b = 3;
  foo();
  d = a+b+c+d;
  .
  .
  .
}
```

```
void foo(){
  int a,b,c;
  c = 4;
  .
  a = 2; b = 3;
  foo(c-1,b+1);
  a = a + b;
  .
  .
  b = 4;
  foo(b,9);
  b = a - b;
  .
}
```

ee ee er

but argument don't cross the boundary

a b

a b

for a:
① if caller. do one save & store for each call : 2+2=4
② if callee: only do save & store at the beginning and end of function: 1+1=2
So. "a" use callee

for b:
① if caller : 2+2=4
② if callee: 1+1=2
So "b" use callee

for c:
since it's not live through the function call.
So we use caller

LEGv8 ABI - Application Binary Interface

- The ABI is an agreement about how to use the various registers. These can be broken into three groups
  - Some registers are reserved for special use Register usage definitions
    - (X31) zero register, (X30) link register, (X29) frame pointer, (x28) stack pointer, (X16-18) reserved for other uses.
- Callee save: X19-X27 9
- Caller save: X0-X15 16
  - In addition, we pass arguments using registers X0-X7 (and memory if there are more arguments)
  - Return value goes into X0

Logistics

- There are 3 videos for lecture 6
  - L6_1 – Assembly_Functions
  - L6_2 – Registers_Caller/Callee
  - L6_3 – Caller/Callee-Examples
- There is one worksheet for lecture 6
  1. Caller/Callee-saved registers